TWELVE YEARS OF SOFT EXCESS FROM CLUSTERS

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OUTLINE

1. Early observations with EUVE and ROSAT
2. Recent observations with BeppoSAX, ROSAT, XMM-Newton, Chandra and Suzaku
3. The oxygen emission line puzzle ...
4. The HI problem ...
5. Summary of observational status
6. Interpretation: Thermal vs. non-thermal models
7. Prospects for the future

1. Early detections with EUVE and ROSAT

- Discovery of EUV excess in the Virgo cluster with EUVE (60–200 eV), Lieu et al. (1996)
- Interpreted as 0.1–0.5 keV plasma

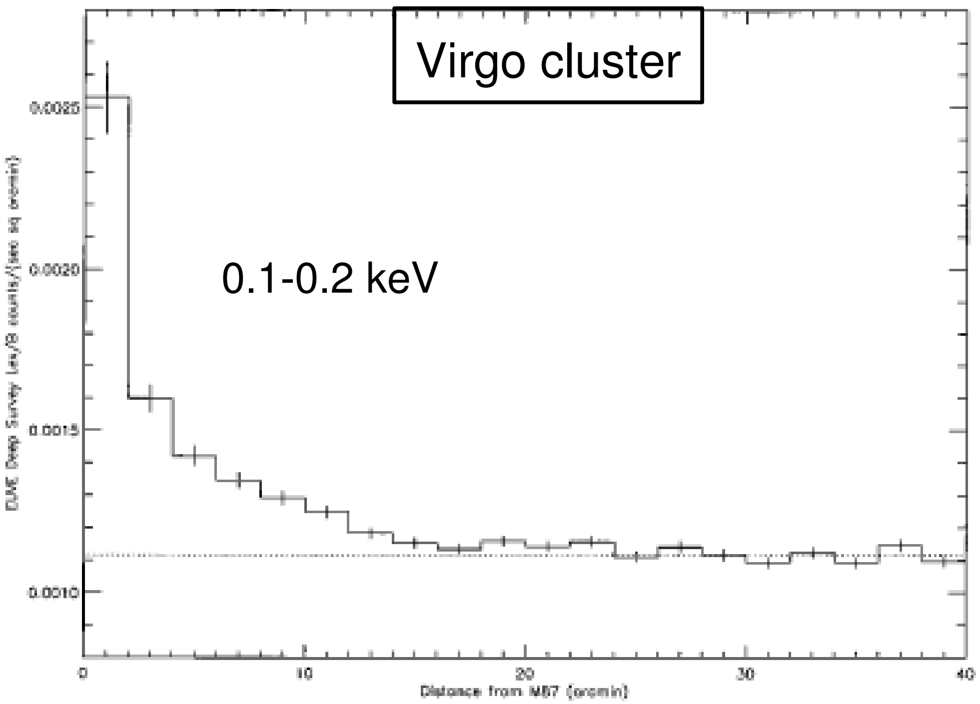


FIG. 1.—*EUVE* DS Lex/B filter count rates for concentric annuli centered at M87. Data from the innermost 2′ region are consistent with a point source. The region between 2′ and ~20′ corresponds to a diffuse excess (the EUV halo of M87). The background level is marked by a dotted line.

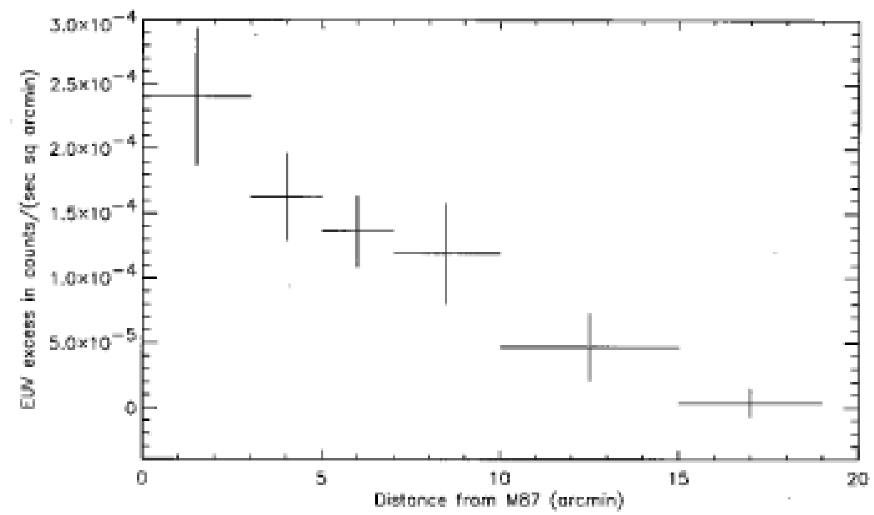
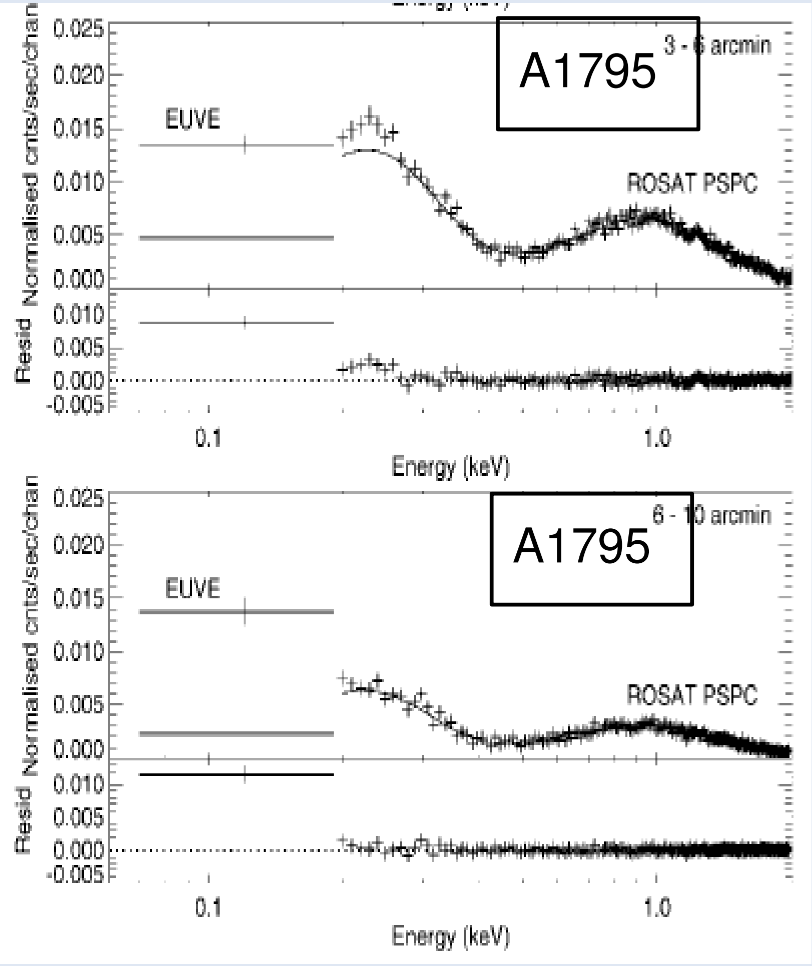
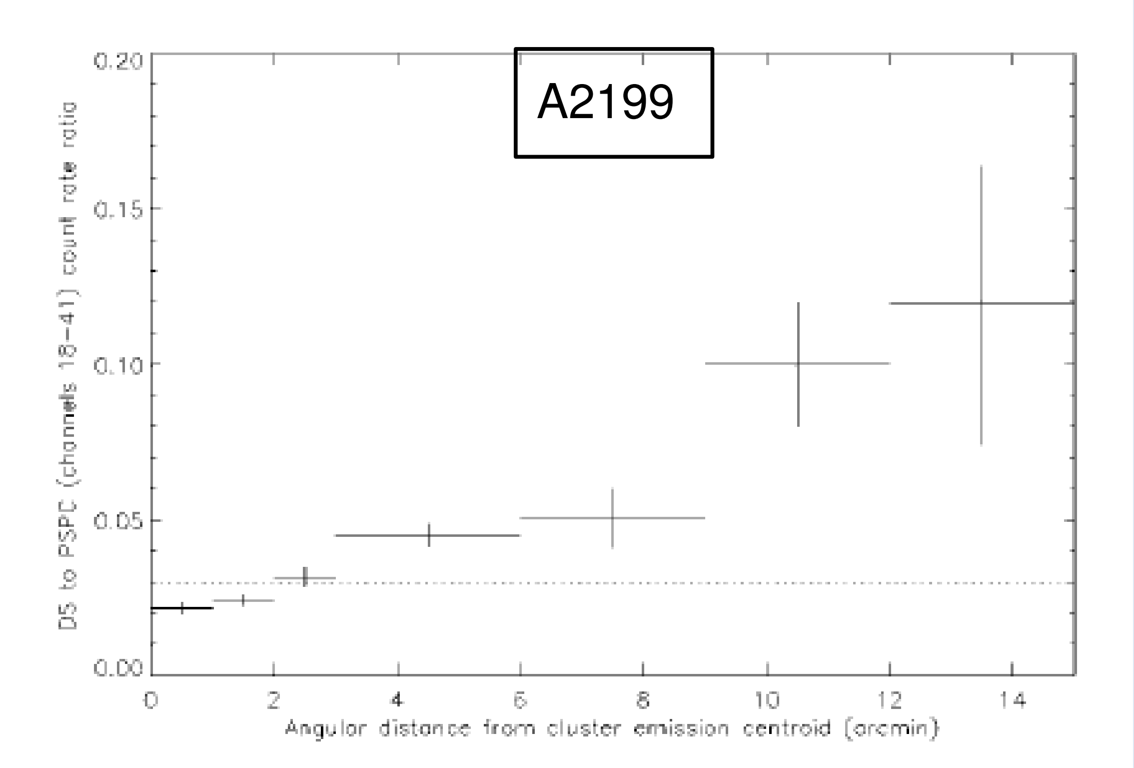


FIG. 3.—Radial profile of the surface brightness of "EUV excess," defined as the amount of diffuse emission within the DS Lex/B band above the best-fit single-temperature plasma model obtained by simultaneously fitting the DS data and the 0.18–2 keV PSPC data.

• Detection of excess emission from ROSAT and EUVE in A1795, Mittaz et al. (1998)
• EUVE detection of excess in A2199, further indication of increasing trend of excess with radius (Lieu et al. 1999)





• Bowyer et al. (1999): EUVE confirms excess in Coma, excess disputed in A2199 and A1795
• Differences mainly based on background subtraction (...more later...)

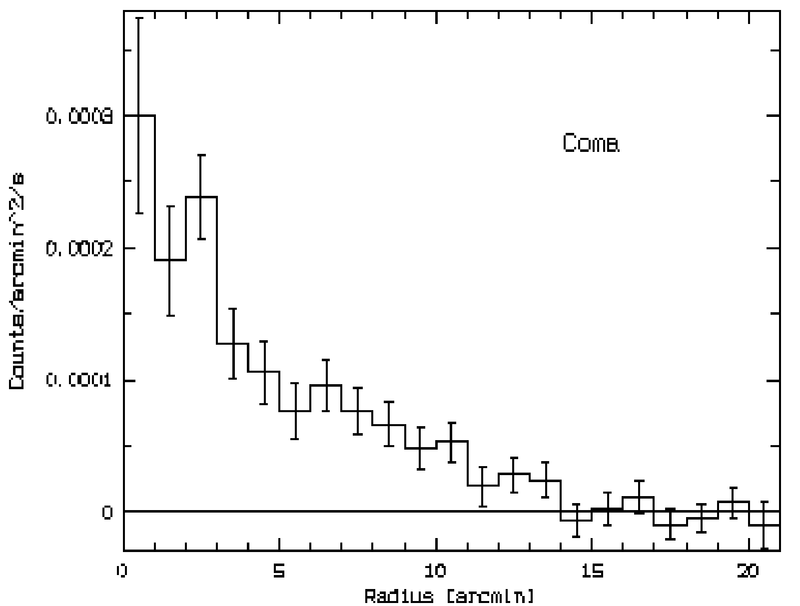


FIG. 10.—Excess EUV emission in the Coma Cluster

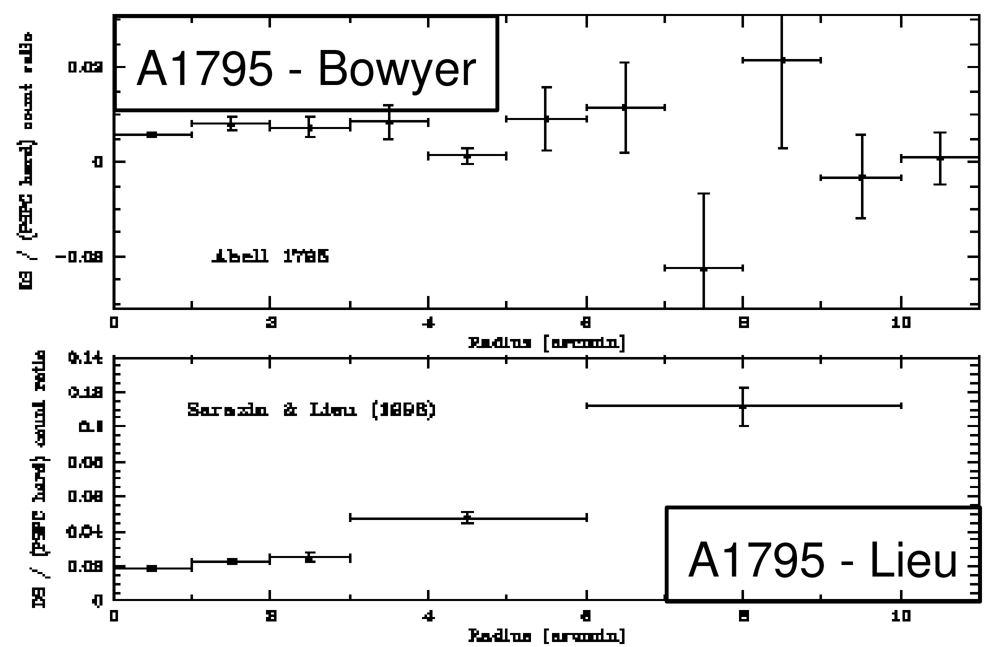


FIG. 6.—(*a*) Ratio between our background-subtracted EUV radial emission profile obtained with the *EUVE* DS and the X-ray profile obtained with the *ROSAT* PSPC. (*b*) DS to PSPC count rate ratio as a function of radius obtained by Mittaz et al. (1998) and used by Sarazin & Lieu (1998).

• Overall EUVE excess challenged by Arabadjis and Bregman (1999) based on new He cross-section calculations
• Always used the *lowest* (e.g., most conservative) values.

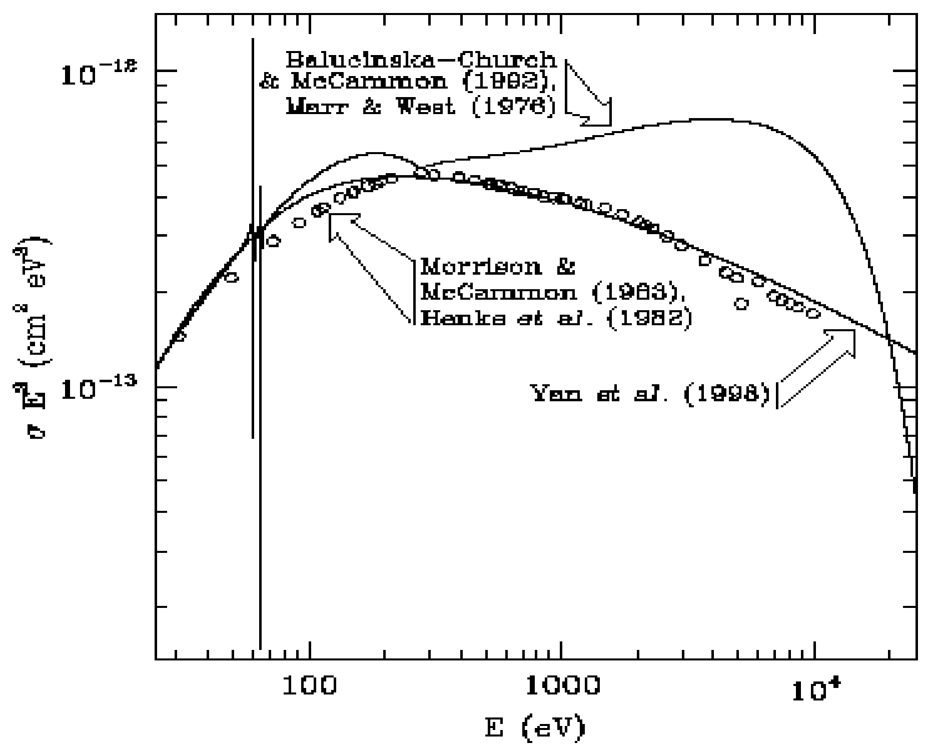
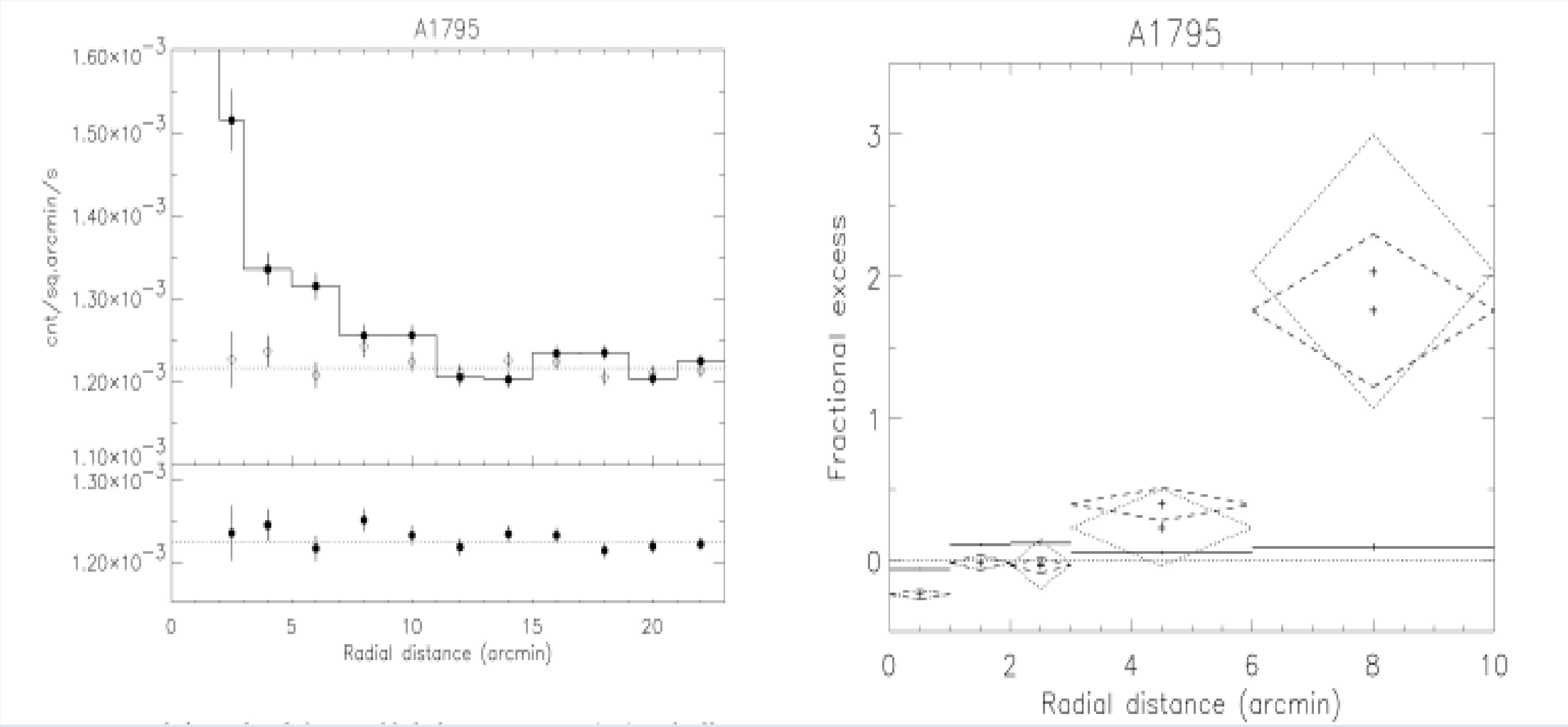


FIG. 1.—Comparison of neutral helium cross sections. The autoionization features near $E \sim 60$ eV are shown only for the Bałucińska-Church & McCammon (1992) cross sections. These are not relevant to our models, however, since the fitting range of this study is 0.14–2.0 keV.

He cross-sections

• Morrison and Mc Cammon (1983) **wabs**
• Balucinska-Church and Mc Cammon (1992) **phabs**
• Yan et al. (1998), slightly lower than MM83
• Wilms et al. (2000) **tbabs**, identical to MM83

- Re–observations with EUVE of Virgo and A1795 show the radial trend (Bonamente et al. 2001)
- Use of in–situ background for background subtraction



- Realization of a possible non-thermal origin of the soft excess (Hwang et al. 1997; Sarazin and Lieu 1998; Bowyer et al. 1998)
- IC scattering off CMB requires relativistic electrons

$$\langle\gamma\rangle \approx 300 \left(\frac{\langle h\nu_{\rm EUV}\rangle}{75\ {\rm eV}}\right)^{1/2} .$$

- Non-thermal content in clusters can be estimated – CR e- may carry several % of the hot gas pressure

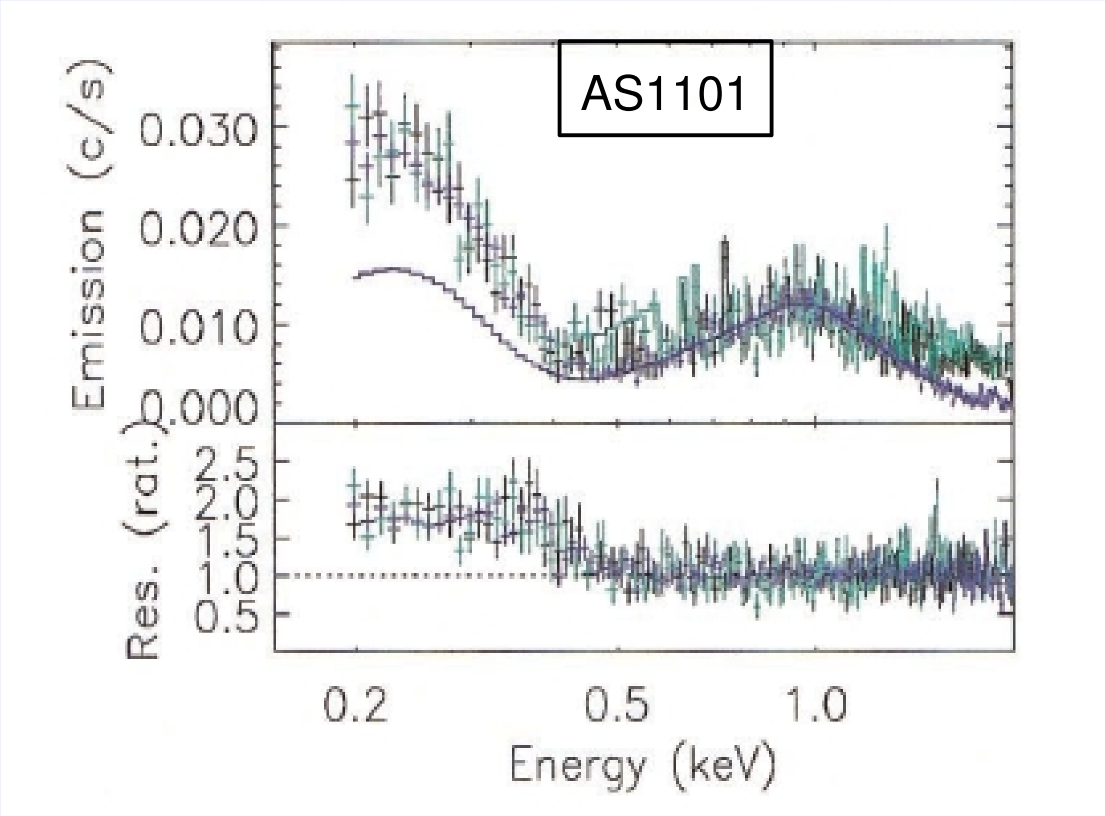
$$E_{\rm CR} \approx 2.4 \times 10^{62} \left(\frac{L_{\rm EUV}}{10^{45}\ {\rm ergs\ s^{-1}}}\right)\left(\frac{\langle\gamma\rangle}{300}\right)^{-1} {\rm ergs.}$$

Lessons learned from early observations

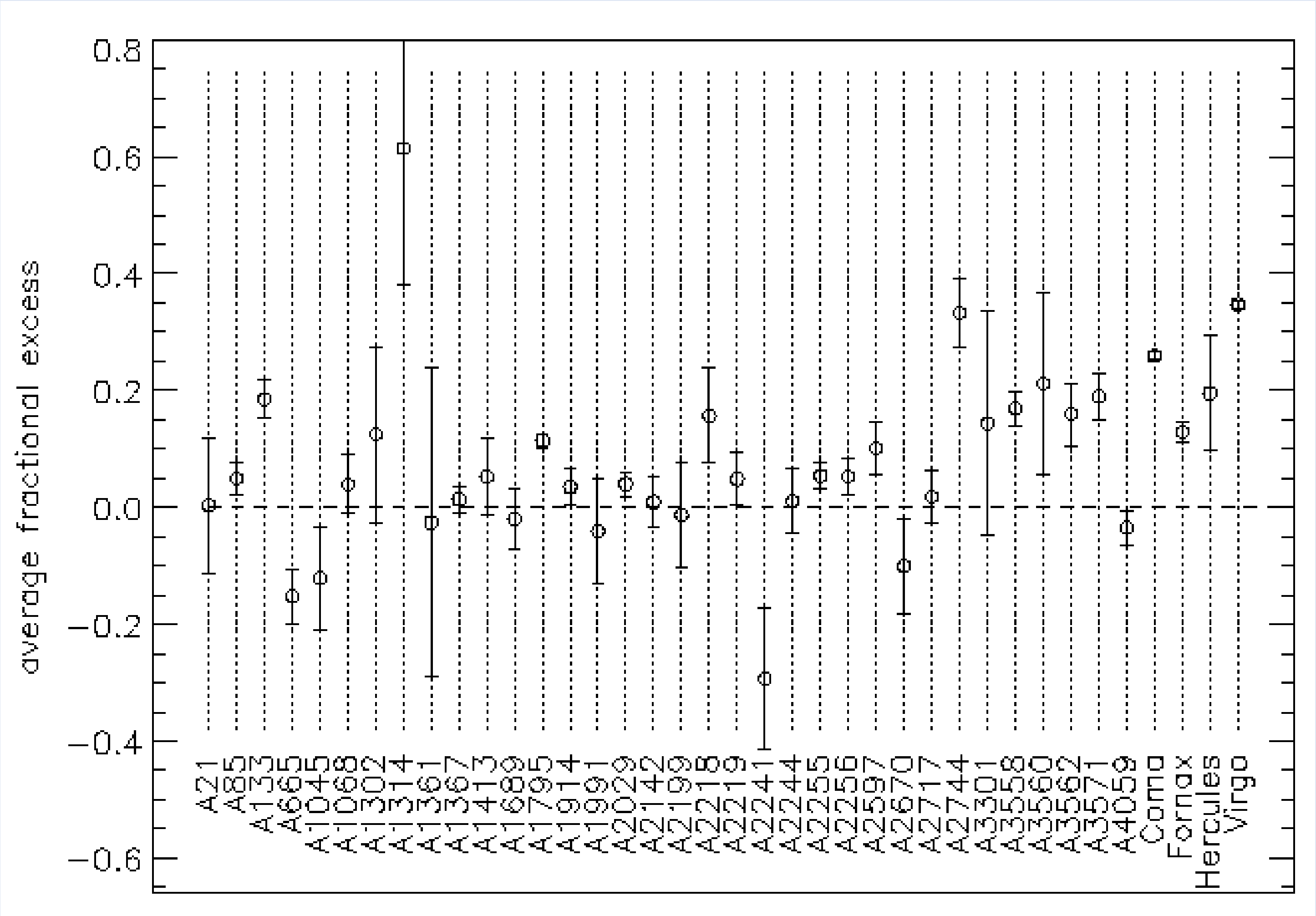
1. Very soft X-ray excess emission above the hot gas
2. Detection relies on Galactic HI column density and understanding of the He cross-section
3. EUVE data analysis challenged
4. Excess emission can be explained with warm gas (0.1-0.5 keV) or with relativistic CR electrons inverse-Compton scattering the CMB
5. Estimates of mass and energy budgets for the soft excess emitter largely uncertain at this point

2. Recent observations with ROSAT, BeppoSAX, XMM, Chandra and Suzaku

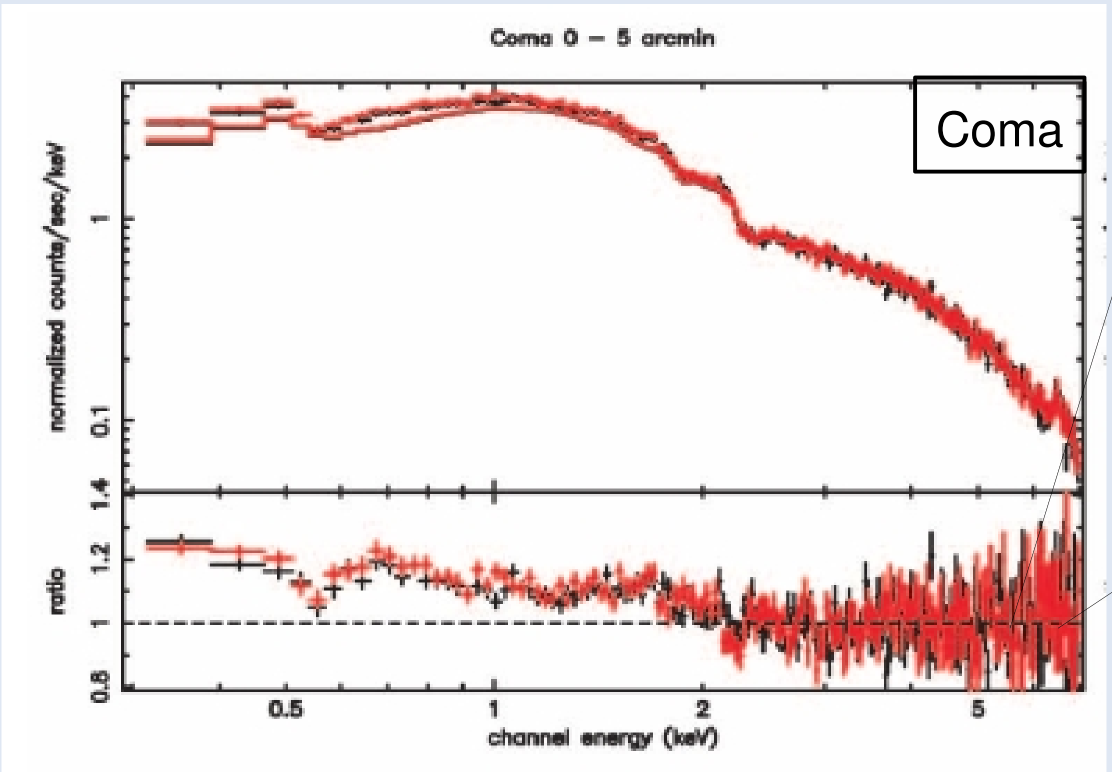
- Detection of soft excess in Shapley supercluster members with ROSAT and BeppoSAX (Bonamente et al. 2001a)
- Detection of soft excess in AS1101 (aka Sersic 159-03) with ROSAT – first soft excess cluster with 100% excess in C band (Bonamente et al. 2001b)

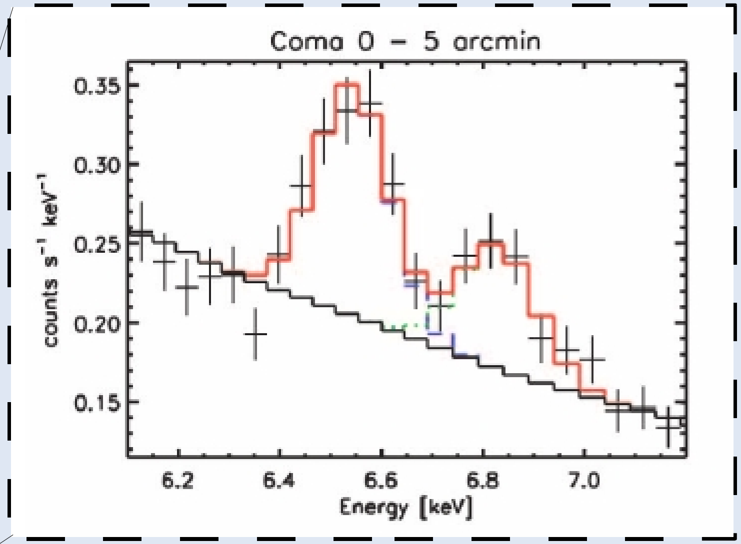


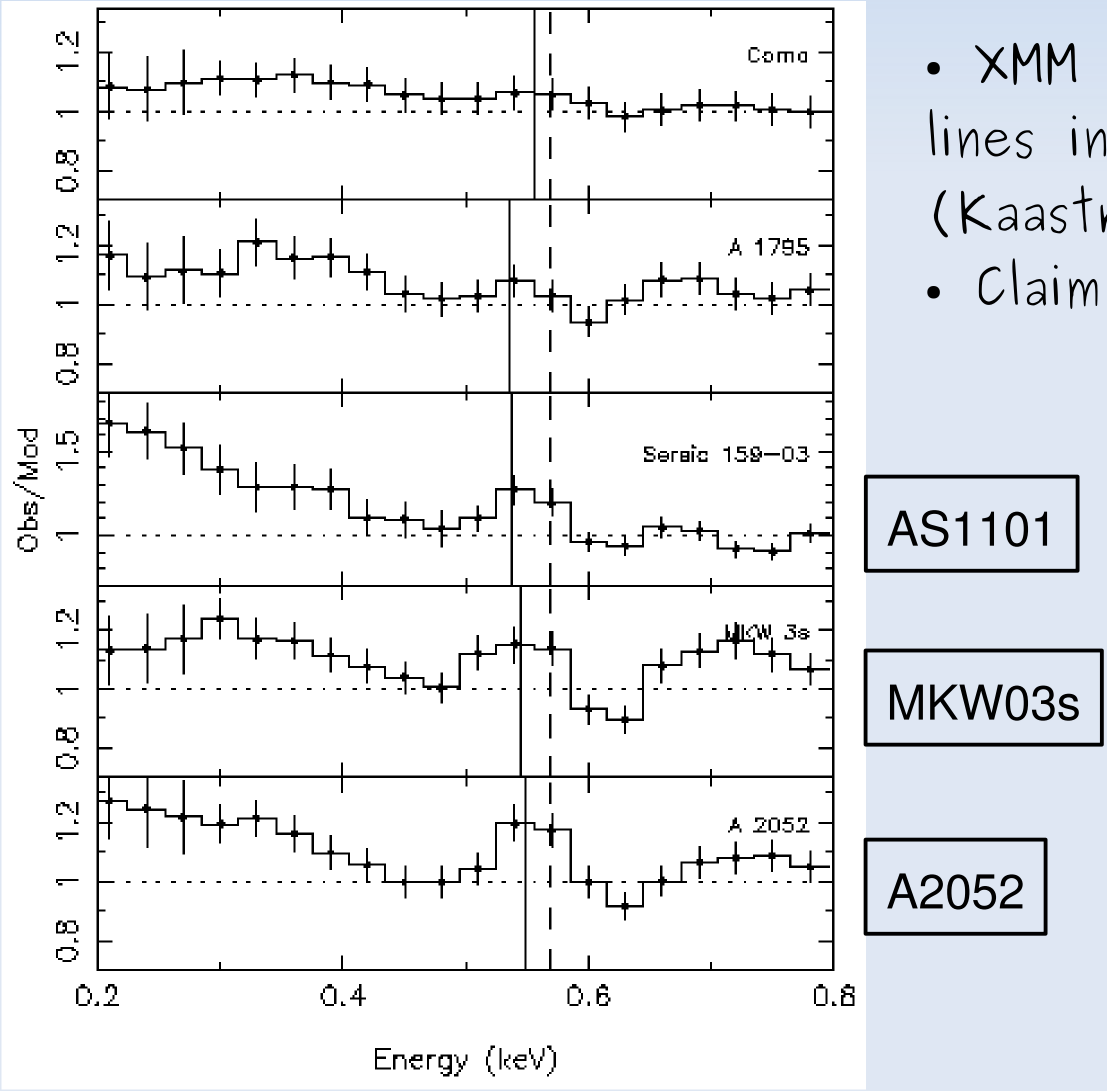
• Analysis of a 38-cluster sample at high Galactic latitude with ROSAT
– 50% have excess in C band (Bonamente et al. 2002)



- XMM detection in Coma, A3112 (Nevalainen et al. 2003)
- Excess confirmed, extended to >1 keV energies

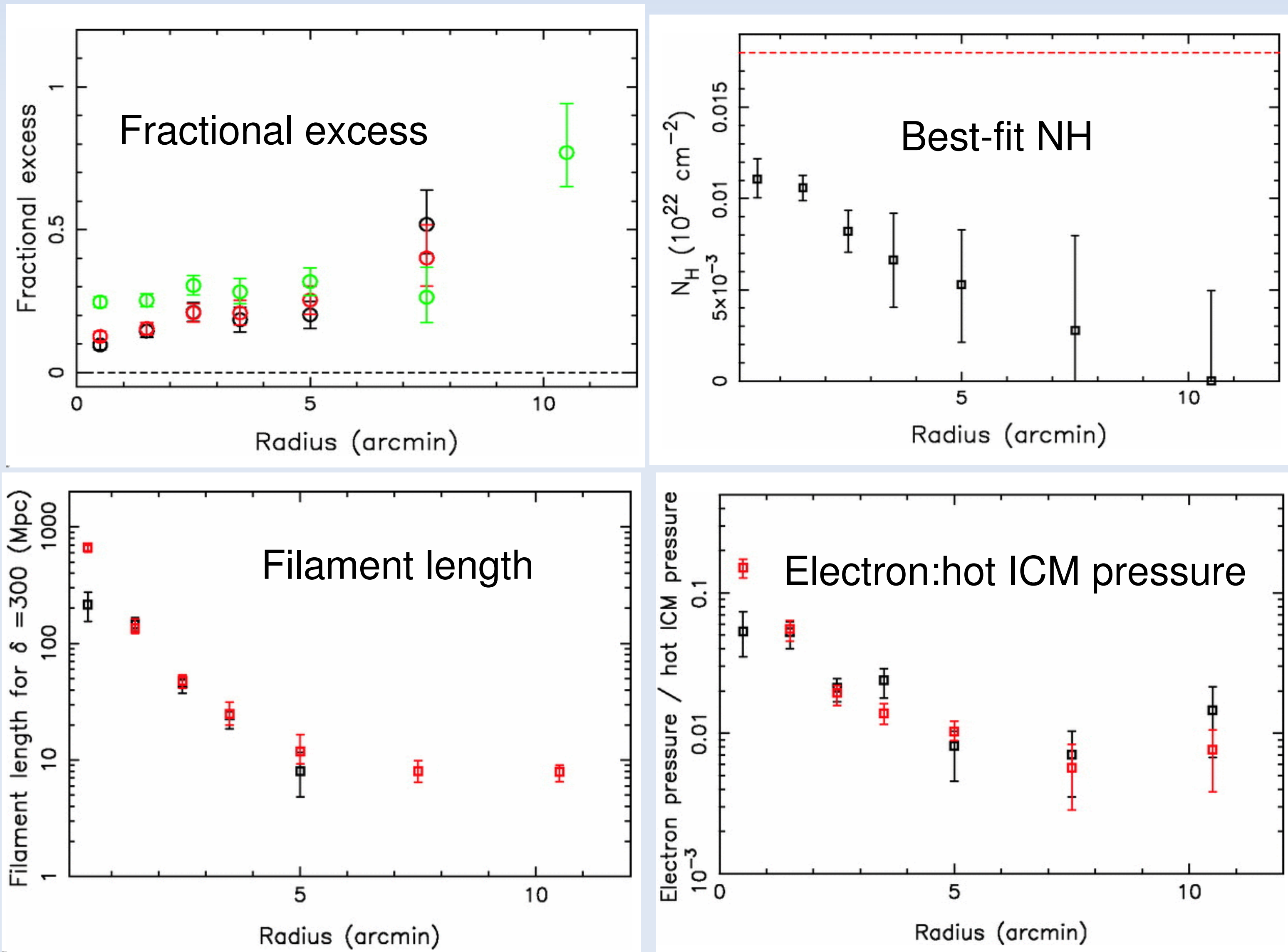






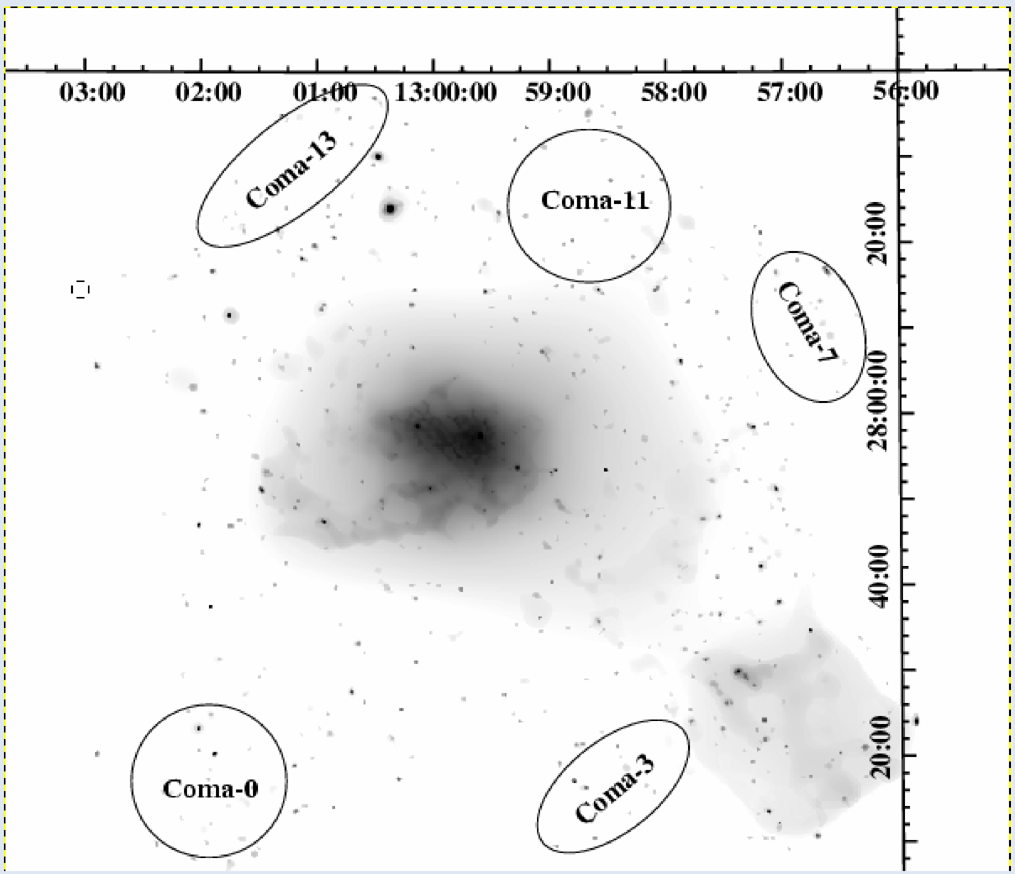
- XMM detection of OVII emission lines in A2052, MKW03s and AS1101 (Kaastra et al. 2003)
- Claim of cluster origin

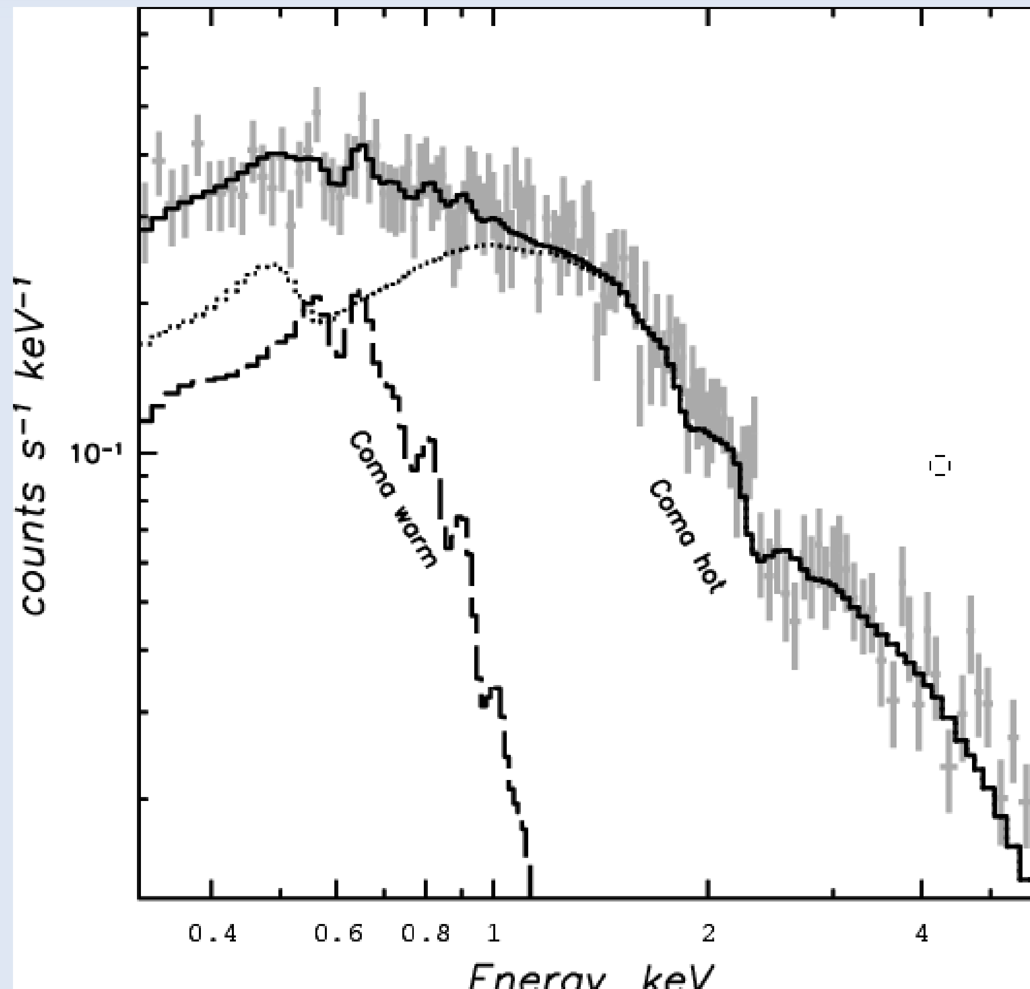
- XMM detection of soft/hard excess in AS1101 (Bonamente et al. 2005)
- Thermal interpretation as filaments leads to excessive estimates



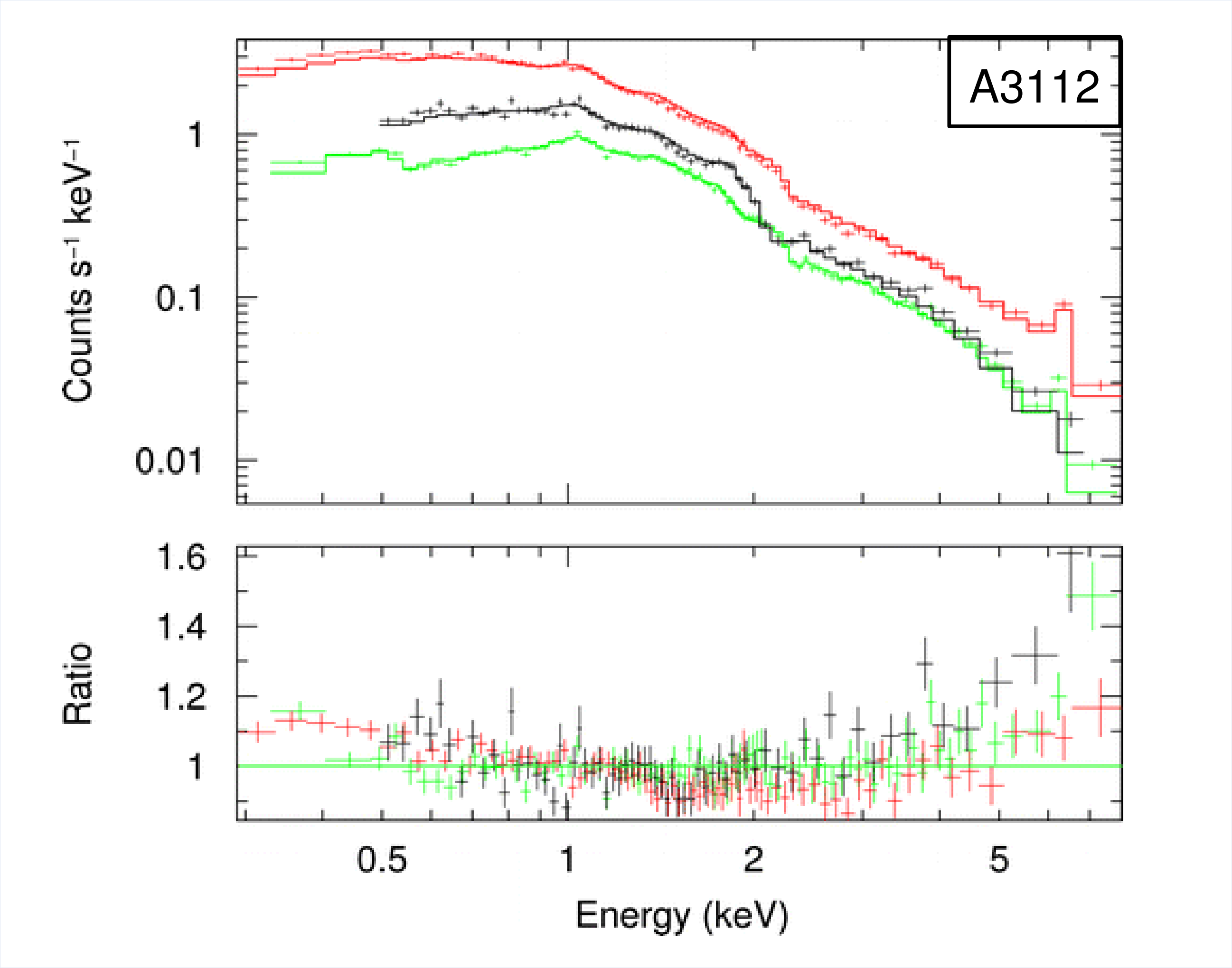
AS1101

- Finoguenov et al. (2003) detects a filament in Coma11 field from XMM data, with associated OVII emission

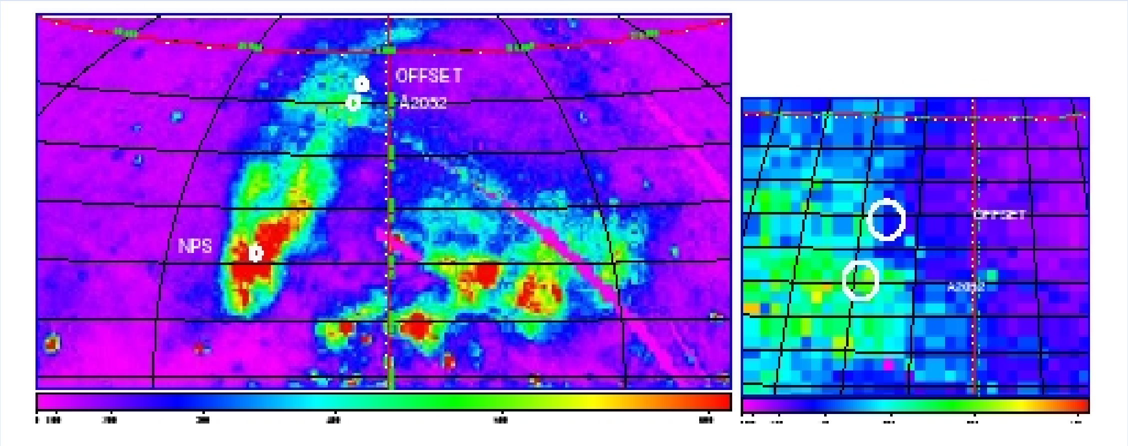


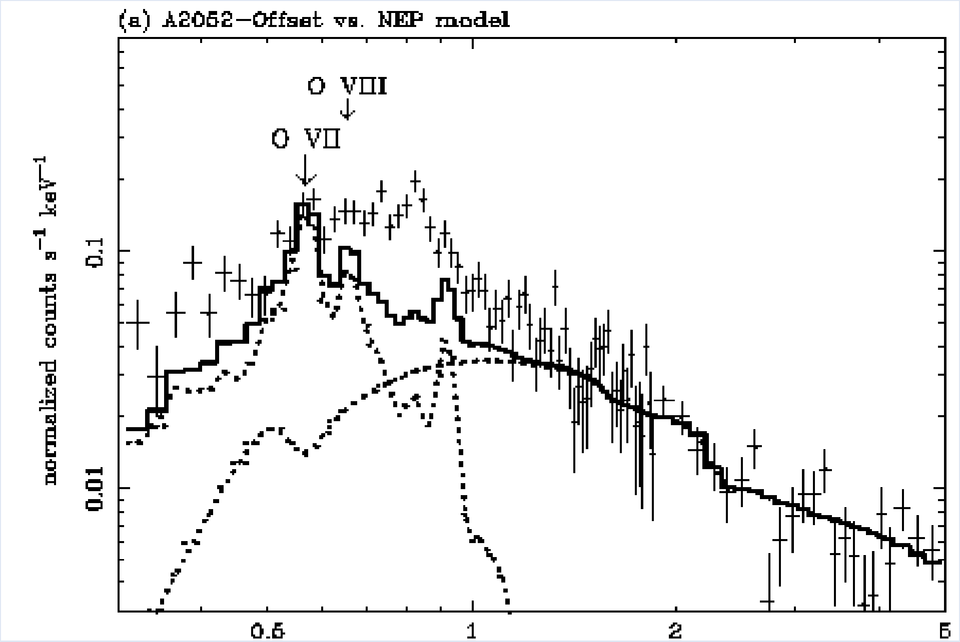


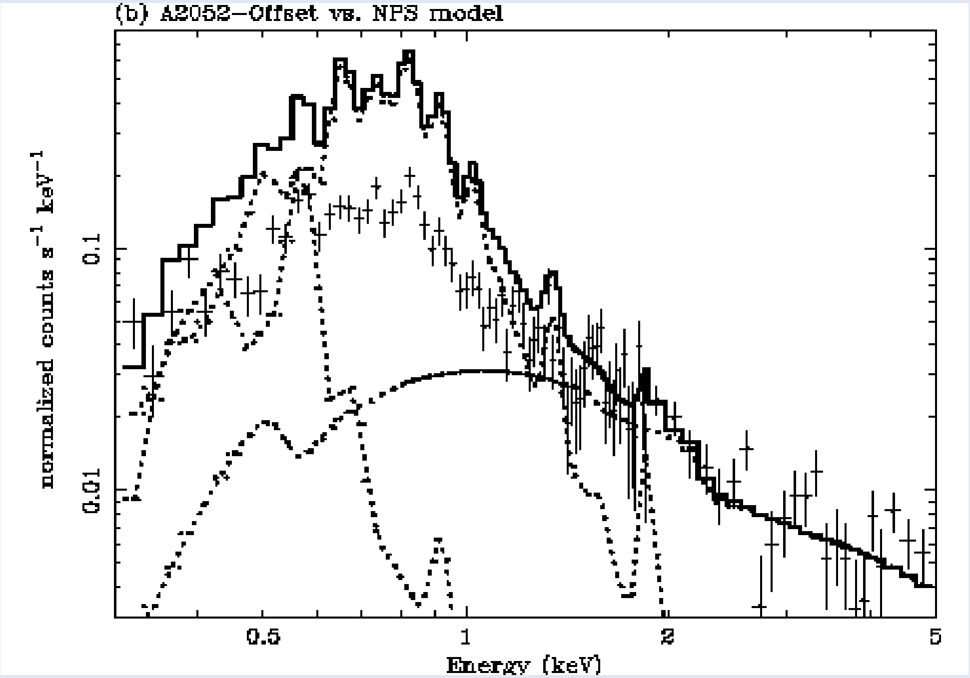
- Chandra detects the excess too (Bonamente et al. 2007)
- Possible connection soft/hard excess in A3112 and A754(Henriksen et al. 2004)



- Suzaku detects `excess' in A2052 (Tamura et al. 2008)
- Excess interpreted as Galactic excess or cluster soft excess







3. The oxygen emission line puzzle

- Takei (2008) observes Coma-7 and Coma-11 (plus local background)
- No soft excess, OVII emission lines are due to solar activity!

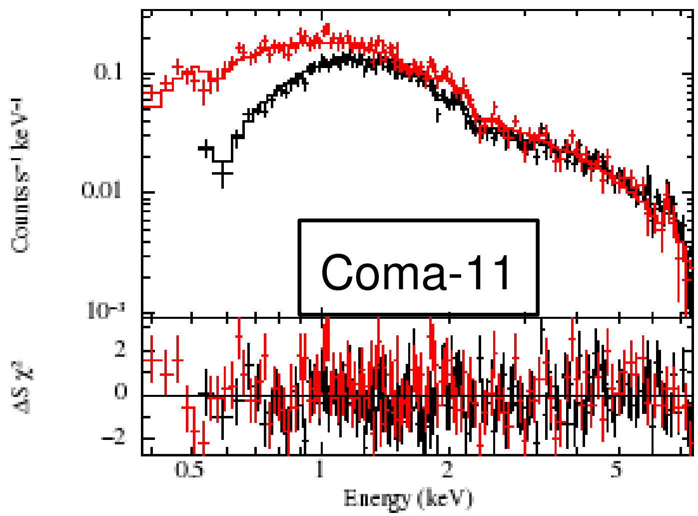
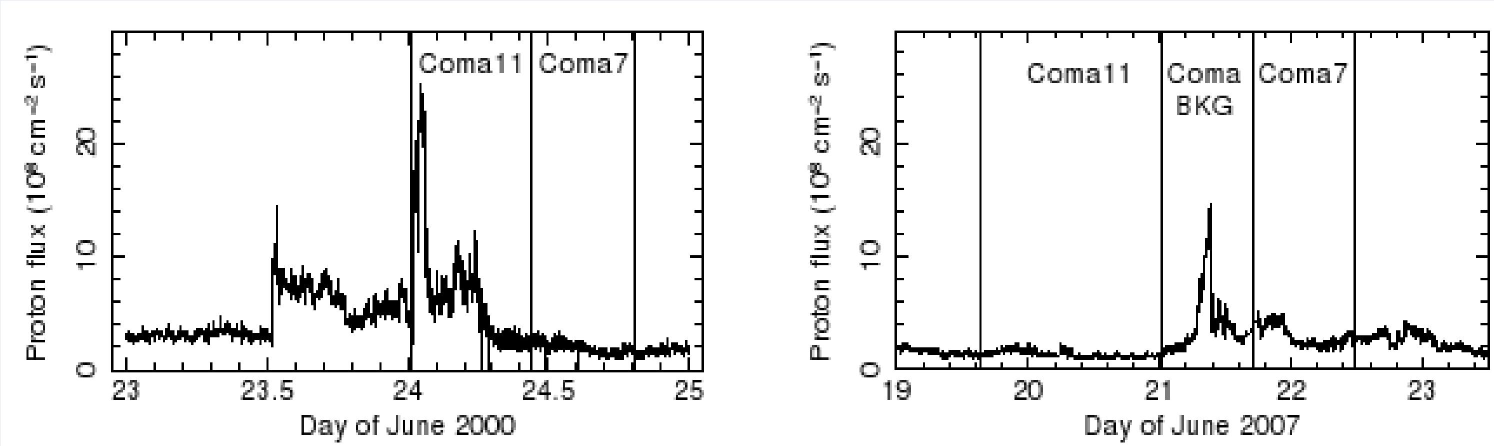
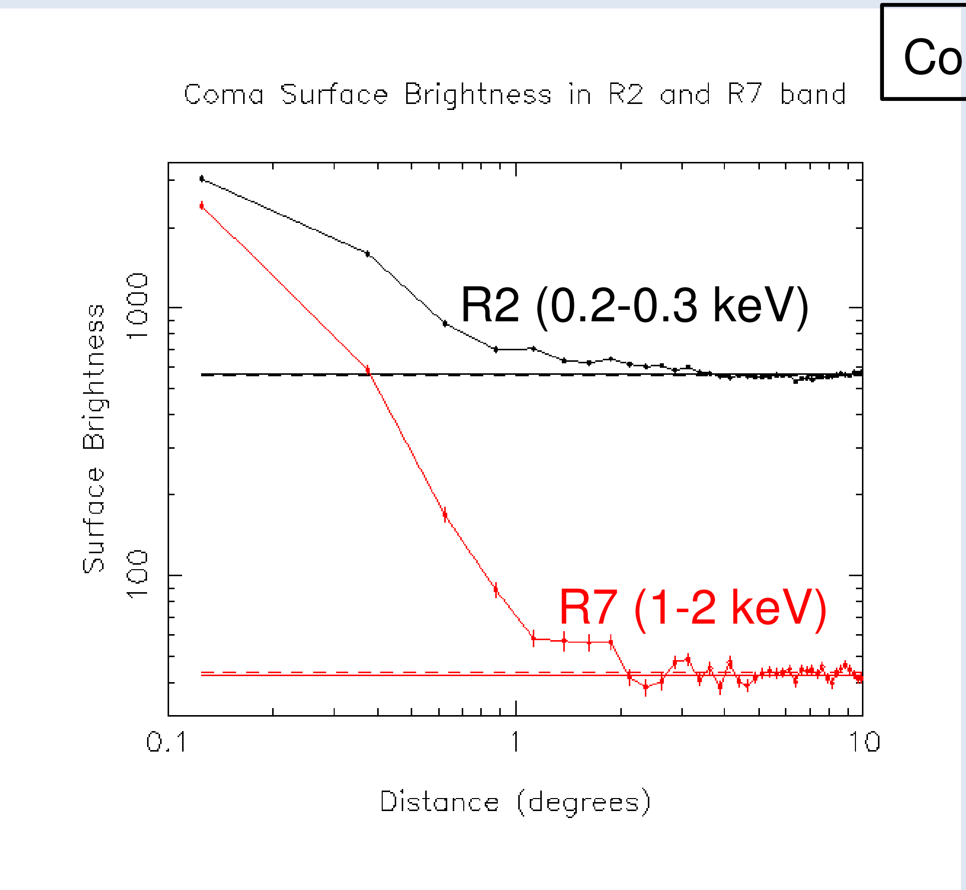


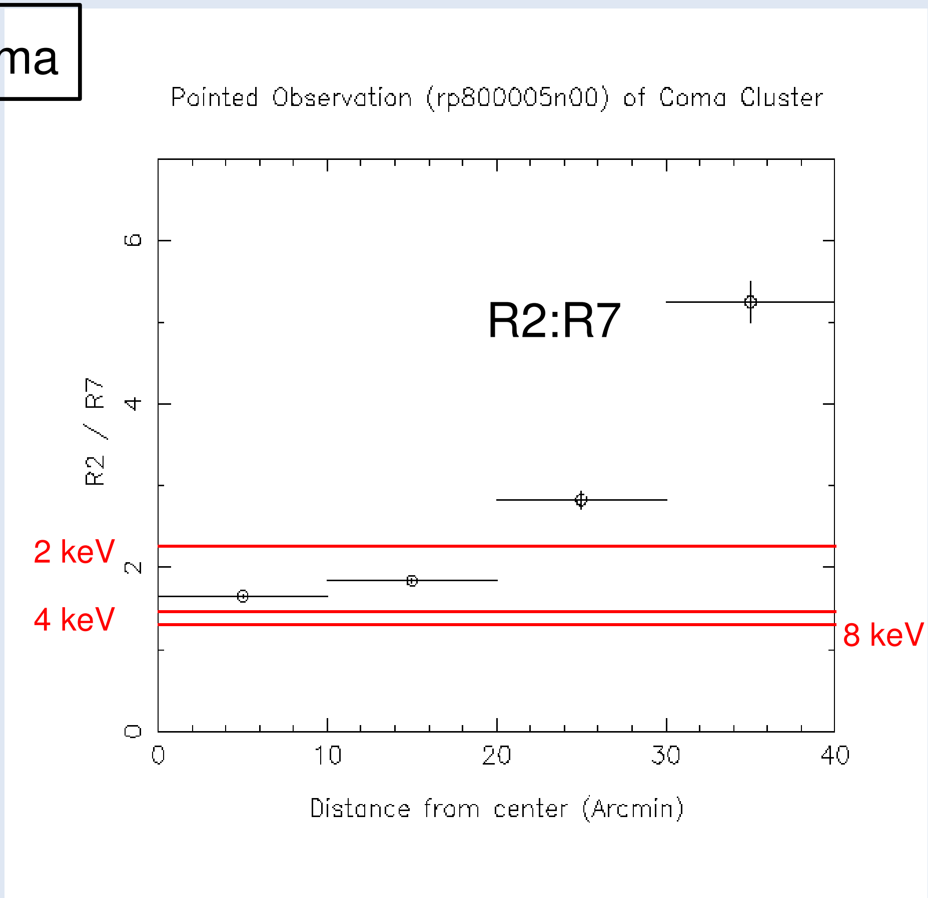
FIG. 2.— Spectra of Coma-11 (left) and Coma-7 (right). Red and black data correspond to BI and FI respectively. ComaBKG spectra were subtracted to correct the background emission.



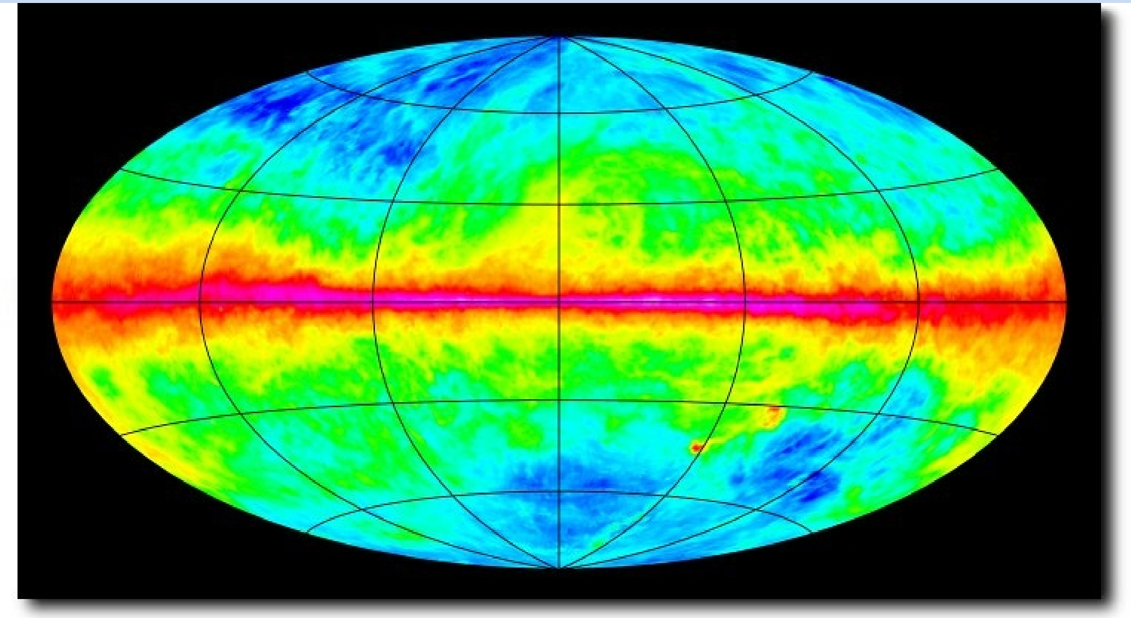
- Bulbul et al (2008 in prep.) reanalyzed the Coma ROSAT data
- Confirmed the presence of soft excess – unaffected by background variability

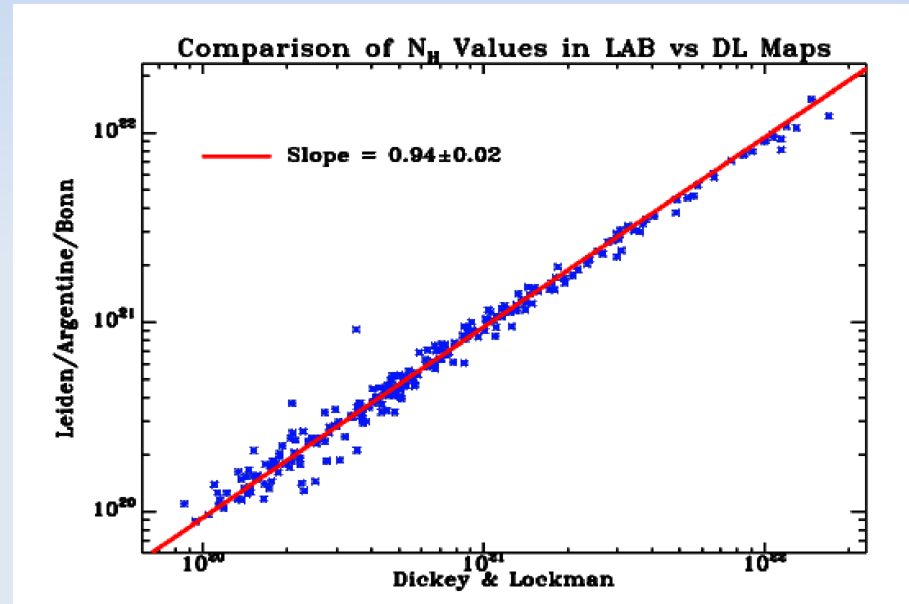
Coma





4. The HI problem ...





Notable differences:

- **A3112**

DL >> Weighted average nH (cm**-2) 2.61E+20
LAB >> Weighted average nH (cm**-2) 1.33E+20

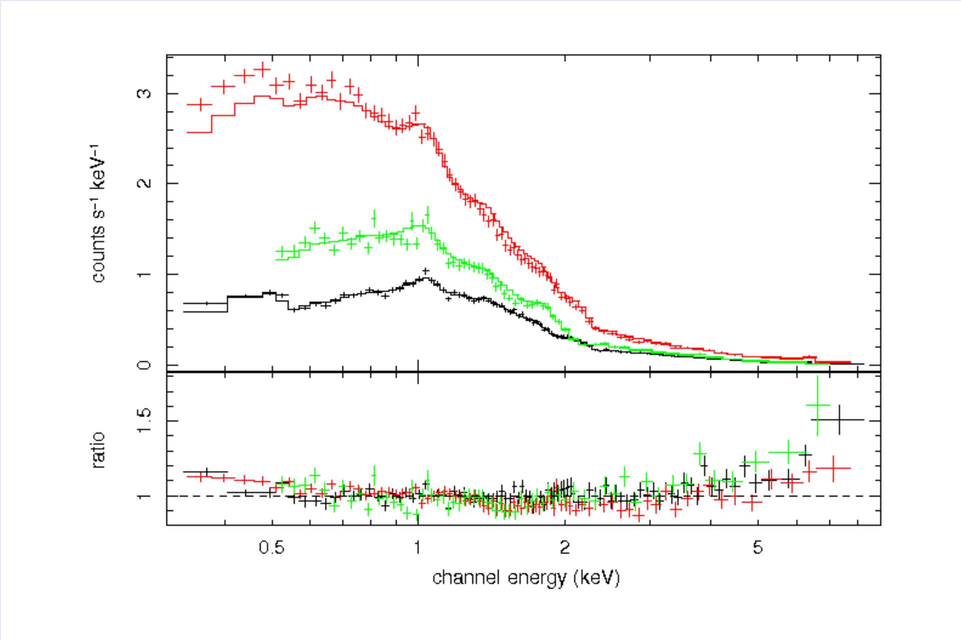
- **AS1101** (Sersic 159-03)

DL >> Weighted average nH (cm**-2) 1.79E+20
LAB >> Weighted average nH (cm**-2) 1.14E+20

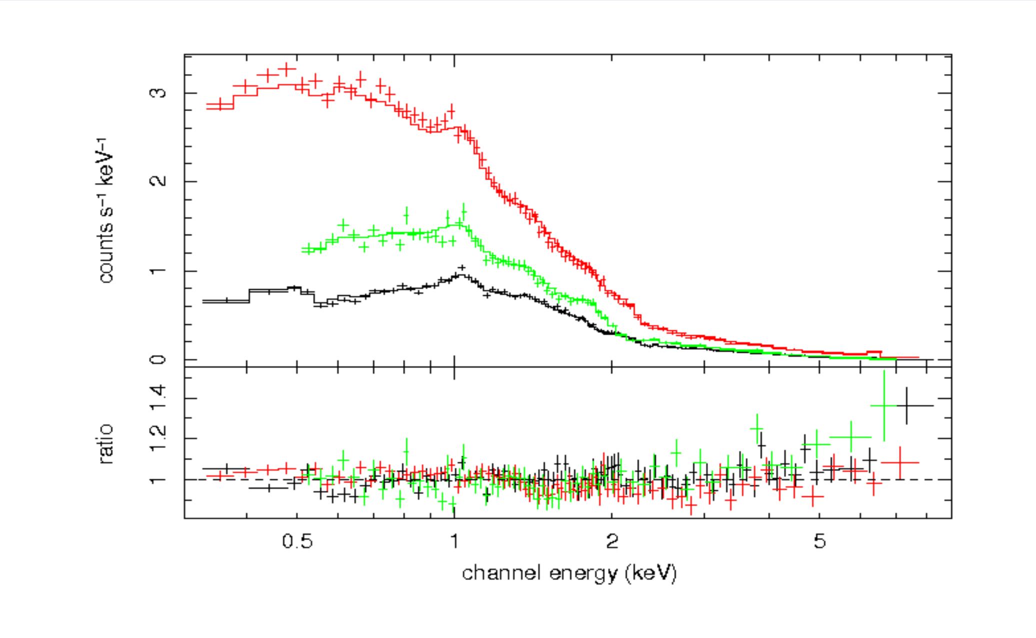
- So ... is all the soft excess gone ? (you know the answer...)
- Joint Chandra/XMM data of A3112, 1–2.5' region, full-band fit:

A3122

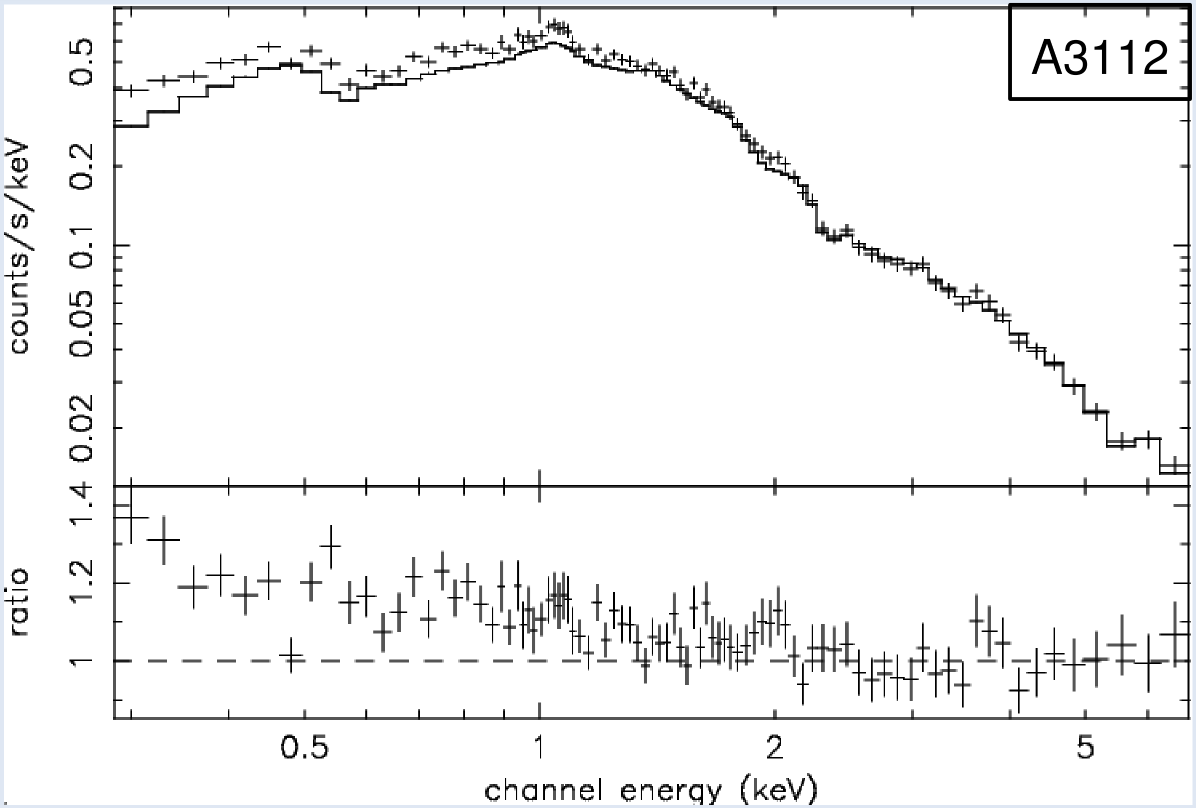
DL



LAB



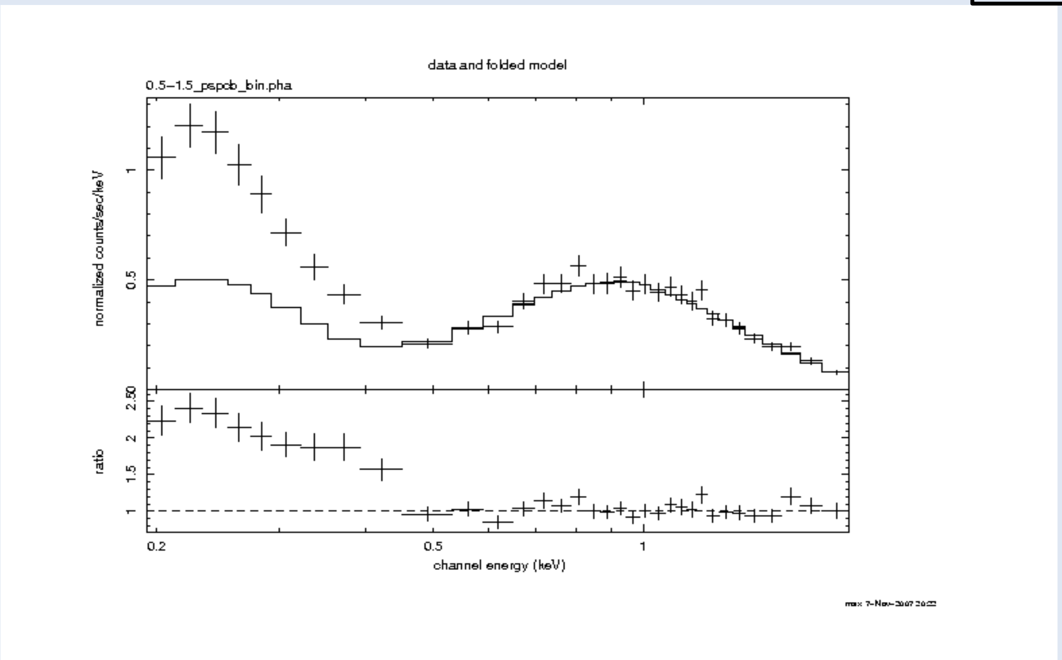
- XMM data of A3112, 1.5–2.9' region, fit to 2–7 keV (Durret et al. 2007)



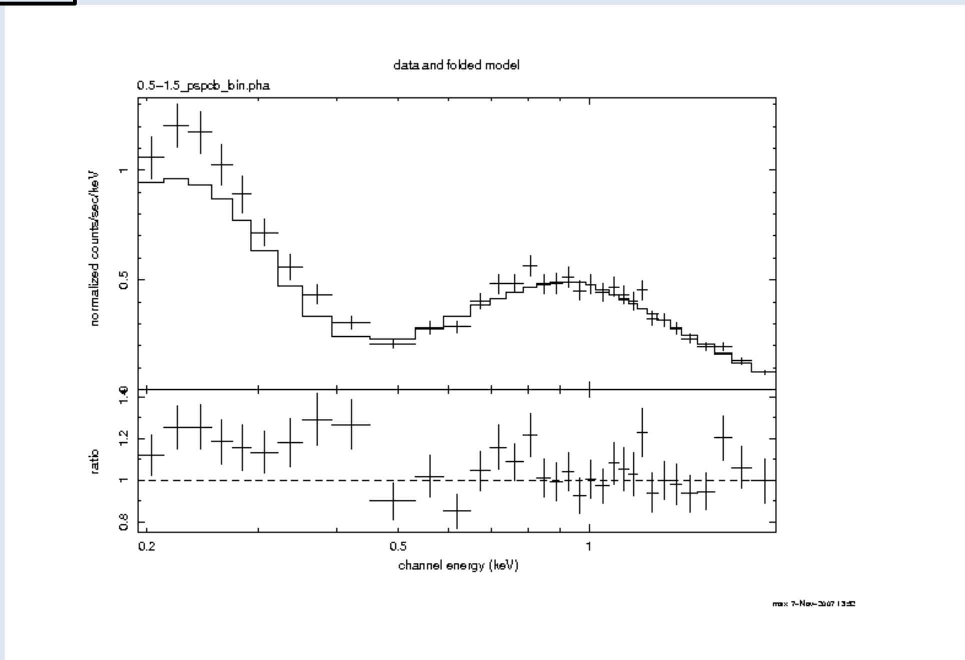
- A3112, ROSAT data, 1–2,5' region, 0.5–2 keV fit

A3112

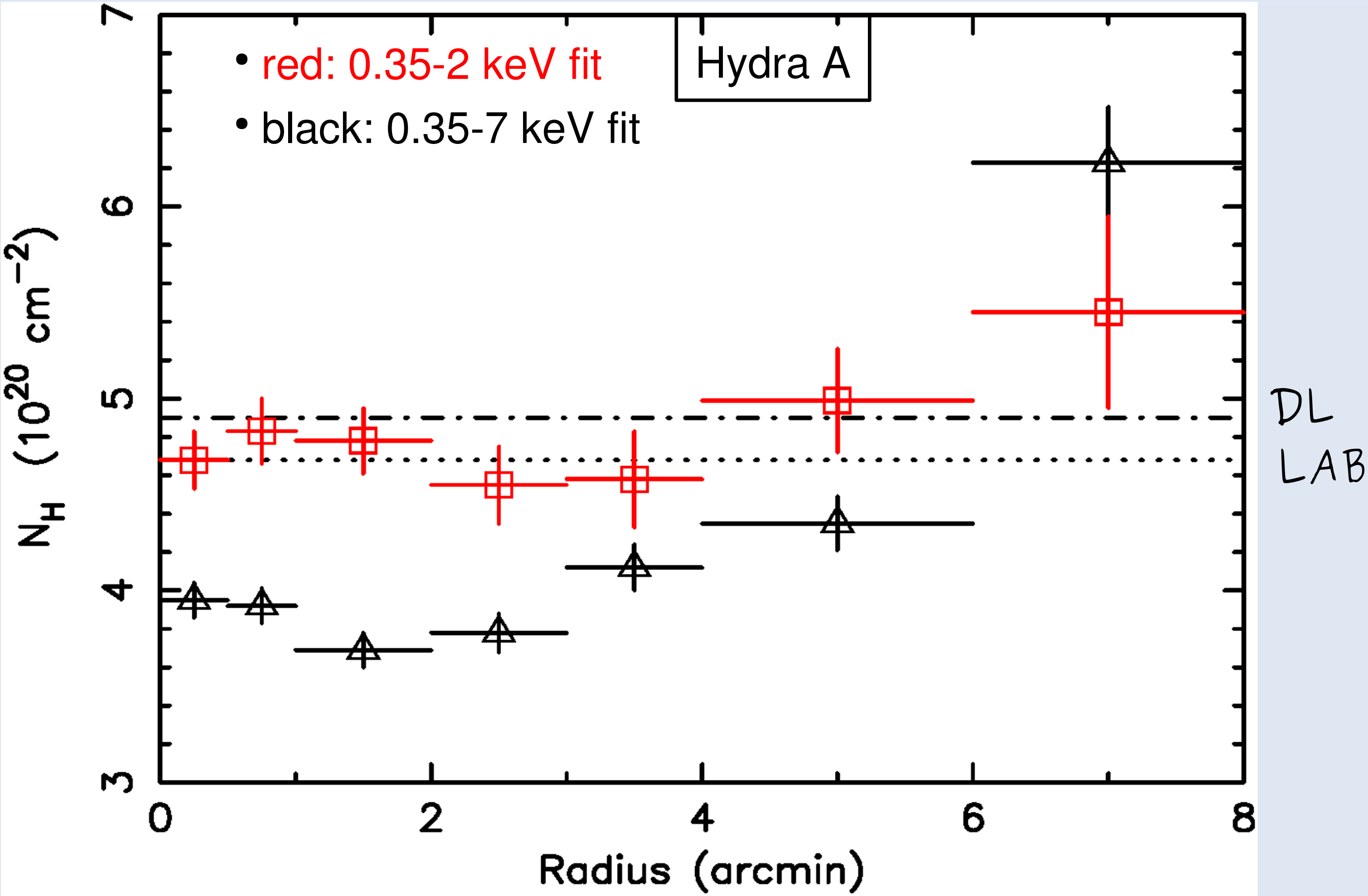
DL



LAB



- AS1101, 3–8' region, Suzaku+XMM data (Werner 2008)
- Excess in Hydra A, XMM data, from Simionescu et al. (2008) in prep.



5. Summary of observational status

- Soft excess above the C band challenged
- Emission lines associated with soft emitter challenged

- C band excess in ROSAT confirmed: soft excess is <u>soft</u>
- Soft excess cannot be due to HI if a **radial trend** with radius is observed ...
- In situ background necessary for analysis

- Most comprehensive review of observations: Durret et al. (2008)

6. Interpretation: Thermal vs. non-thermal models

- Thermal interpretation
  1. Diffuse warm gas with high volume filling factor
  2. Warm gas in pressure equilibrium (low filling factor)
  3. Filaments projecting onto clusters (WHIM)

- Non-thermal interpretation
  1. Diffusive shock acceleration: inverse Compton scattering with the CMB
  2. Other localized acceleration events (such as AGN's) with subsequent diffusion

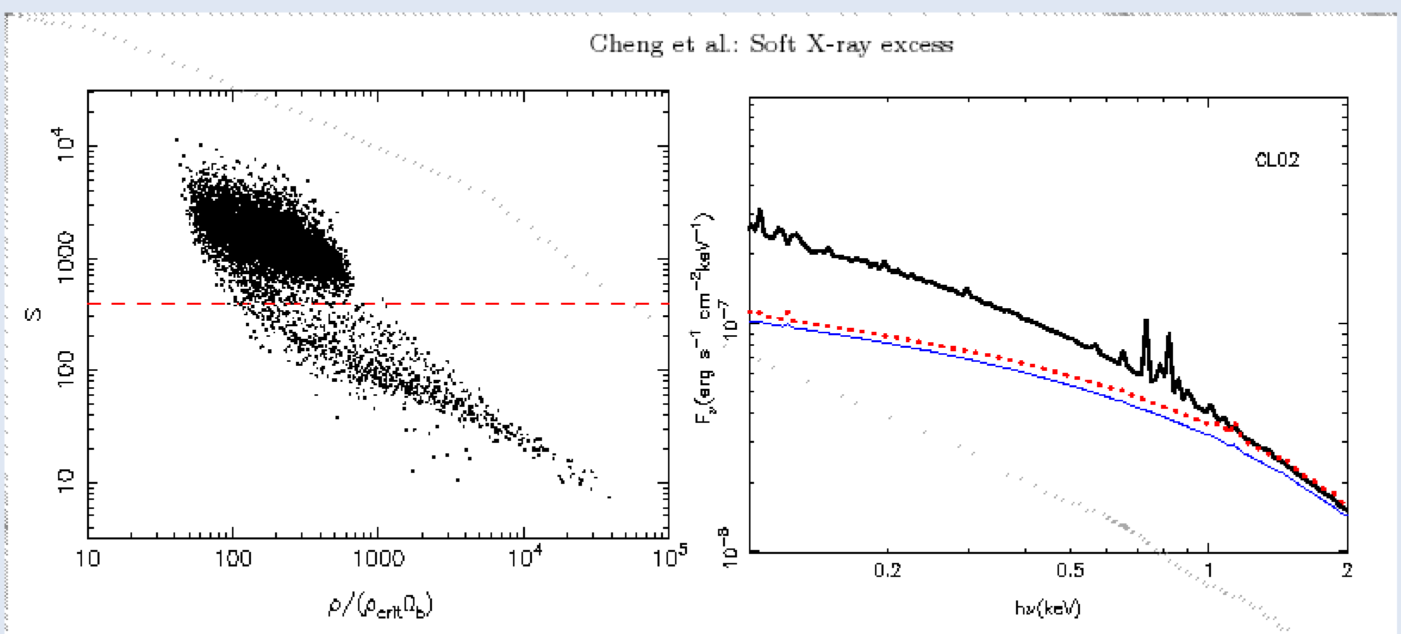
Thermal interpretation
1. Diffuse warm gas with high volume filling factor

- Warm halo can be as massive as the hot ICM (Coma: Bonamente et al 2003): UNPHYSICAL
- Cooling time may be less than the Hubble time:

$$t_{\rm cool} \simeq 6 \times 10^9 \left(\frac{T}{10^6\ {\rm K}}\right)^{1/2} \left(\frac{n}{10^{-3}\ {\rm cm}^{-3}}\right)^{-1}\ {\rm yr}$$

Thermal interpretation
2. Warm gas in pressure equilibrium (low filling factor)

- Mass requirements are reduced
- Warm gas may be sustained at the interface of cold clouds in the ICM (Fabian 1997)
- Require a dynamical model, since cooling time of the gas is reduced further; simulations of Cheng et al. (2005)



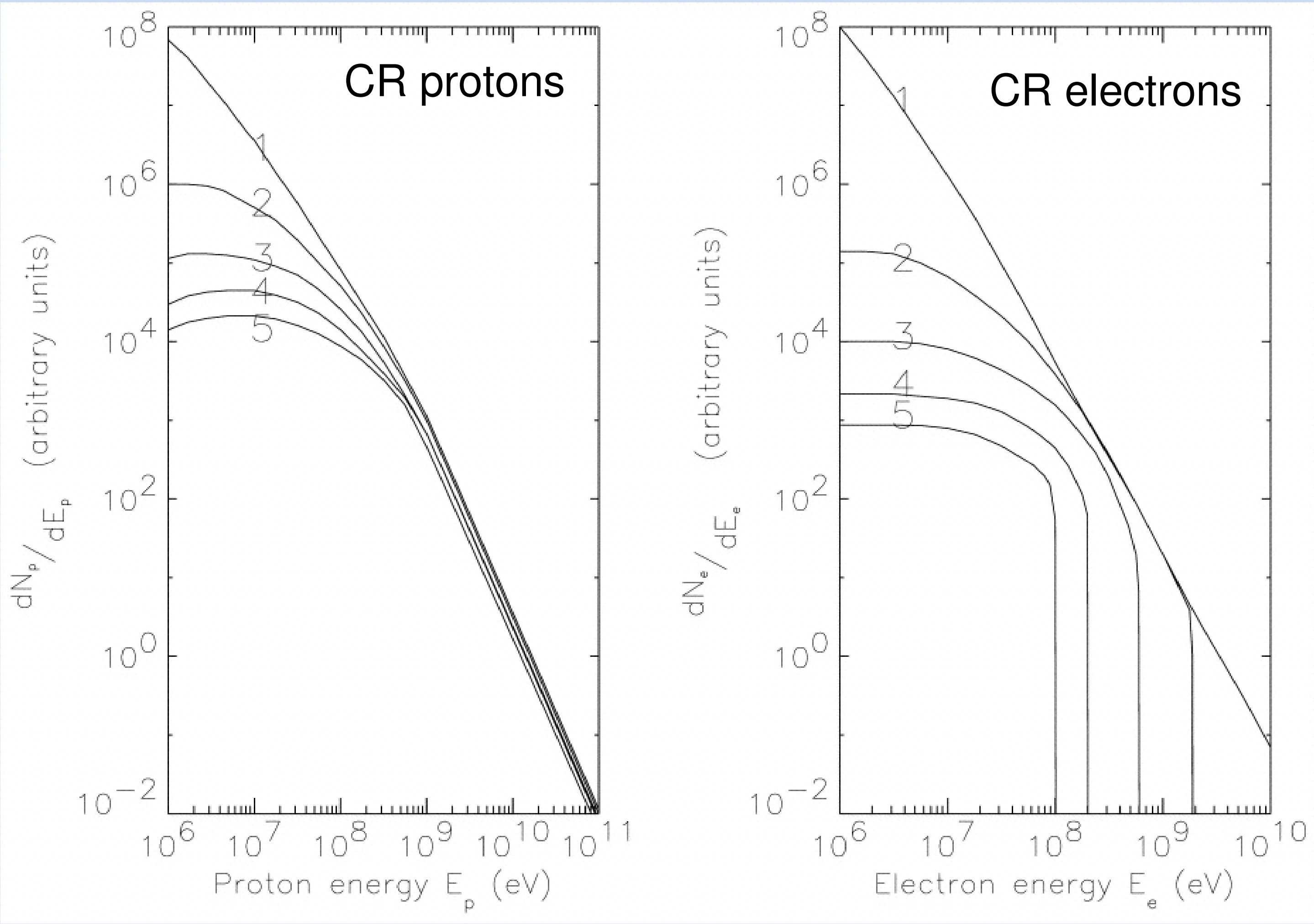
Thermal interpretation
3. Filaments projecting onto clusters (WHIM)

- Introduced by simulations of Cen and Ostriker (1999), Dave et al. (2001), Fang et al. (2002)
- Detected excess was found by Mittaz et al. (2005), Bonamente et al. (2005) to require filaments of length and density in excess of theoretical predictions
- Reduction in soft excess intensity may make the model viable again ...

Non-thermal interpretation

1. Diffusive shock acceleration: inverse Compton scattering with the CMB

- Model proposed by Hwang et al. (1997), Sarazin and Lieu (1998), and others;
- Requires relativistic electrons of Lorentz factor $\gamma = 300–500$
- Relativistic ion may accompany the electrons (e.g., Lieu et al. 1999), resulting in non-thermal pressure 10–100% of the hot ICM



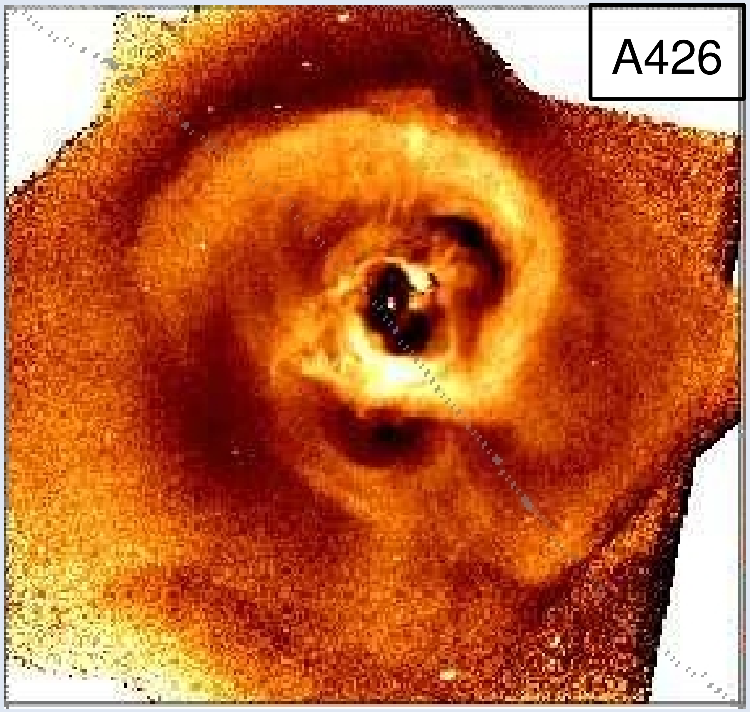
(Lieu et al. 1999)

- Connection with hard excess emission (Fusco-Femiano et al. 1999, and many more)

Non-thermal interpretation

2. Other localized acceleration events (such as AGN's) with subsequent diffusion

- Non-thermal activity in cluster well established
  - Radio halos and relics
  - Interaction between AGNs and ICM seen in A426 (Sanders and Fabian 2007)



7. Prospects for the future

- Analysis:
  - Understand the time variability of the X-ray background
  - Understand HI in the Galaxy

- Theoretical progress:
  - Connection between soft and hard excess to study non-thermal origin (Hard X-ray imaging needed)
  - Can the filament model be made viable?

- Future missions:
  - Emission/absorption lines: eV-class spectrometers
  - Upcoming missions with C-band sensitivity/calibration: EDGE, eRosita